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Relationship between soil water content and soil particle size on typical slopes of the Loess Plateau during a drought year

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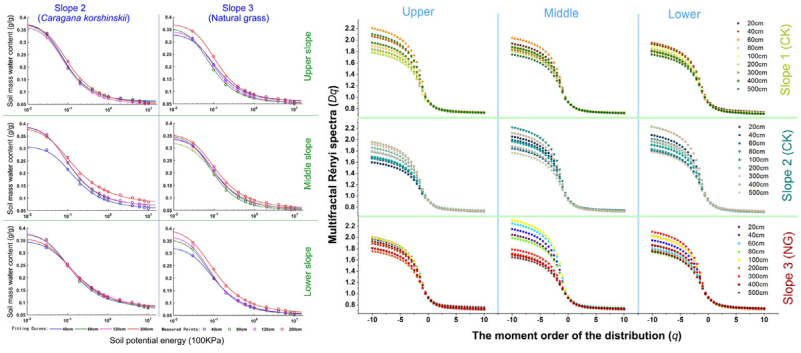
HIGHLIGHTS

- Fractal dimension analysis is a useful tool for understanding hydropedology.
- Shrub and grass used soil water below 2 m and 1.2 m respectively in a drought year.
- Shrub reduces erosion of fine particles but consumes water stored in deep layers.

GRAPHICAL ABSTRACT



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ABSTRACT

In the context of global climate change as well as local climate warming and drying on the Loess Plateau of China, understanding the relationship between soil particle size and soil water distribution during years of atypical precipitation is important. In this study, fractal geometry theory is used to describe the mechanical composition and texture of soils to improve our understanding of hydropedology and ecohydrology in the critical zone on the Loess Plateau. One grassland slope and two shrubland slopes were selected in the hilly and gully region of the Loess Plateau, and soils were sampled along hillslope transects at depths of 0–500 cm. Fractal theory and redundancy analysis (RDA) were used to identify relationships between the fractal dimension of soil particle-size distributions and the corresponding van Genuchten parameters for the soil-water-characteristic curves. The oven-drying method was used to measure soil water content, and the high-speed centrifugation method was used to generate soil-water-characteristic curves. The results show that (1) the soil water that can be used by *Caragana korshinskii* during a drought year is distributed below 2 m from the surface, whereas the soil water that can be used by grass is below 1.2 m; (2) *Caragana korshinskii* promotes the conservation of fine soil particles more than does natural restored grass, and the soil particle-size distribution fractal dimension changes with depth and position; and (3) soil hydraulic properties correlate strongly with soil pedological properties such as bulk density and the soil particle-size distribution fractal dimension. These results provide a case study of the relationships among soil distributions, hydrologic and geomorphic processes for vegetation restoration in drylands with

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a thick vadose zone. More studies on soil property changes are needed to provide case studies and empirical support for ecological restoration in the Loess Plateau of China.

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1. Introduction

The Loess Plateau of China is a critical area because it occupies a large areas of arid and semiarid areas and feeds a large amount of the country's population; however, the ecosystem is fragile, and the loose soil is easily eroded (Fu et al., 2002; Lü et al., 2012). With global climate change, extreme weather events have increased, and the climate of the Loess Plateau has become drier and warmer. These changes threaten local ecological restoration (Qin et al., 2002, 2014; Stocker et al., 2013). To conserve soil and water and to control desertification of the Loess Plateau, the Chinese government conducted the *Grain to Green* program in 1999. As the area and age of the shrub- and grass-planting areas have increased, the conflict between water consumption by different types of vegetation planted and soil desiccation has become more evident (Lü et al., 2012; Wang et al., 2004, 2010, 2011). The loess hilly and gully region is the key area of soil and water conservation in the Loess Plateau and is home to millions of people (Fu et al., 2002; Wang and Shao, 2000). The soil in this area is loose with strong erodibility, and the landscape is the most fragmented and rugged of all of the areas in the Loess Plateau. The average amount of soil erosion in this region is >2000 t/(km^2 yr) and is even over 20,000 t/(km^2 yr) in the worst areas (Fu, 1989; Shi and Shao, 2000). The precipitation is concentrated in the summer and most of the intensity of the rainfall is strong and erosive. In this region, grasses and shrubs are the most common vegetation types, occupying more than half of the total area (Zhao and Running, 2010). Most commonly, the dominant species of natural restored grassland (from abandoned slope farmland) are forage grasses, and artificial shrubland restoration uses *Caragana korshinskii* (Wang et al., 2009b; Yao et al., 2012). Precipitation is the only source of soil water that can be used by plants in this area (Jiao et al., 2006; Ning et al., 2013; Yan et al., 2015; Yu et al., 2015b). Due to the close relationship between plant growth and soil water content (Wang et al. 2012), studies of soil water under typical vegetation types in this region have changed from focusing on water content to water movement and hydraulic characteristics (Lü et al., 2014a, b; Shao et al., 2006). Soil available water is the water that can be directly used by plants and is therefore a more useful indicator than volumetric water content, particularly in the context of vegetation growth (Fang et al., 2016; Gao et al., 2015; Wang et al., 2013). Soil available water greatly depends on soil texture and structure (Shao et al., 2006). Soil water content is unable to reach field capacity in the semi-arid Loess Plateau because the amount of evapotranspiration is larger than that of precipitation and the loose soil and deep ground water causes soil moisture infiltration into the deep layer. Texture is an important aspect of soil morphology that can impact the ability of the soil to conserve water as well as support root growth, and strongly influences soil hydraulic characteristics and erosion (Gui et al., 2010; Li et al., 2016; Meskini-Vishkaee et al., 2014; Nguyen et al., 2012). Research on the changes in soil water content and soil texture under different land-use types may reveal the relationships between these factors and long-term vegetation restoration in this erodible area.

The soil-water characteristic curve is important for estimating soil hydraulic parameters that are difficult to measure in the field, such as the wilting point. New techniques require specialized equipment, and the acquisition of undisturbed soil samples from deeper soil layers remains difficult on the Loess Plateau (Arya and Paris, 1981; Daly et al., 2015; Nimmo et al., 1987; Nimmo and Mello, 1991). To solve these issues, the estimation of soil hydraulic properties through inverse modeling has become popular, but it is also time- and resource-consuming (Hopmans and Simunek, 1999; Mirus et al., 2009; Vrugt et al., 2008). Many studies have focused on predicting parameters that are difficult to measure directly based on more easily quantifiable parameters (Carsel and Parrish, 1988; Meskini-Vishkaee et al., 2014; Schaap et al., 2001; Vereecken et al., 2010). The models used to generate soil-water characteristic curves can be divided into direct-fitting (Brooks and Corey, 1964; Campbell, 1974; van Genuchten, 1980) and indirect-calculation methods (Arya and Paris, 1981; Liu and Xu, 2003; Peng et al., 2014). Among the direct-fitting models, the van Genuchten model has been shown to provide good results for most soils in the loess hilly and gully regions of Loess Plateau (Lai and Wang, 2003; Wang et al., 2009a). Since the concept of fractal dimensions has been introduced to soil science with the development of the laser diffraction technique, soil fractal dimensions have received increasing attention (Kong and Song, 2015; Li et al., 2016; Peng et al., 2015). The volume-based fractal model has been proven to be ideal for evaluating and describing soil hydraulic properties as well as soil physical properties and potential (Jin et al., 2013; Montero, 2005; Posadas et al., 2001; Wang et al., 2011; Yang et al., 2008; Yu et al., 2015a).

Most of the research on the relationship between grass- and shrubland ecosystems at the plot and slope scales has been undertaken during normal years, whereas fewer studies have been conducted during drought years (Liu et al., 2007; Liu et al., 2016b; Wang et al., 2014; Yang et al., 2014a; Zhang et al., 2016a). Due to the stronger evapotranspiration on south-facing slopes, the soil water contents on such slopes are markedly lower than those on north-facing slopes; thus, south-facing slopes are more prone to water deficiency under the same precipitation conditions. In this context, studies of the soil water conditions and soil properties of south-facing slopes under different vegetation types during drought years can provide reference baselines for restoration under future climate change scenarios (Lü et al., 2015; Qiu et al., 2001). In this study, two shrubland slopes dominated by *Caragana korshinskii* and one grassland slope dominated by forage grasses, all of which are south-facing slopes, were chosen as study locations. The soil water content, soil-water characteristic curve, soil available water, soil particle-size distribution, and singular and multiple fractal dimensions of soil particle size were measured or calculated at different positions and depths along the slopes. This study aimed to (1) analyze the distribution of soil water content, soil particle size and relevant parameters along typical slopes of the Loess Plateau in a drought year and (2) analyze the relationship between soil particle dimension and the soil available water content to provide a case study of a semi-arid loess area for vegetation restoration management. The hypotheses of this study were as follows: (1) There are significant differences in the depth of water use between grassland and shrubland in a drought year and (2) the relationship between soil particle fractal dimension and the soil-water characteristic curve varies between types of vegetation restoration and among slope positions and soil layer depths.

2. Materials and methods

2.1. Site description

This study was conducted in Liuping Gully in the Ansai Catchment, Shaanxi, China, which is located along the upper reaches of the Yanhe River and belongs to the typical loess hilly gully region of the Loess Plateau. The longitude and latitude are 108°5′-109°26′E, 36°19′-36°32′N, and the area of the Liuping watershed is 24.26 km^2. The landscape is fragmented, and the gully density is high. The study site is located in a temperate semi-arid continental climate zone, and the spatial and

temporal distributions of the precipitation are uneven both intra- and inter-annually. The precipitation is concentrated in the summer; rainfall from June to September contributes >60% of the annual precipitation. The thickness of loess soil is 50–200 m on the Loess Plateau, and the water table is very deep (usually 30 m to 80 m from the surface soil layer and participating little in soil-vegetation-atmosphere-transfer) (Shao et al., 2015), making the groundwater almost inaccessible to plants. The soil is porous, and the heavy rain in the summer makes the soil prone to erosion.

Three slopes in the Liuping Gully that are typical of shrub and grass slopes in the loess hilly and gully region were chosen for study. The dominant species on slopes 1 and 2 is *Caragana korshinskii*, and the dominant species on slope 3 are *Bothriochloa ischaemum*, *Stipa grandis*, and *Stipa bungeana*. The soil type on all slopes is mainly loessial, and the elevation ranges from 1190 m to 1335 m. The sampling year (2015) was a drought year with a total rainfall of 393 mm, which is 13.7–21.4% less than the multiyear mean precipitation of approximately 450–500 mm (Chen et al., 2008; Zhang et al., 2016a, b). The sampling lasted four days, during which no rain occurred, and the last rain came six days before sampling with an amount of 0.2 mm, which had little impact on the soil water conditions. Therefore, the variation in the soil water content was not affected by precipitation during sampling. Due to the reduced rainfall in drought years, the water content in the shallow soil layers (0–2 m) was very low while that in deep layers was temporally stable; therefore, evaporation had little influence during the sampling period.

2.2. Experimental design

Using Google Earth images, slopes with large areas of shrub or grass were preselected for field study. The reachability, length, vegetation type, vegetation coverage, and vegetation restoration age of the preselected slopes were investigated during a trip to the field. Two shrubland slopes and one grassland slope in Liuping Gully were chosen from the preselected slopes as they are typical in the research area. In addition, the two kinds of slopes are close to one another, which avoids the influence of precipitation or other environmental factors in the analysis. Nine sampling points were established from the foot to the top of each slope. In this study, CK denotes for *Caragana korshinskii* shrubland, and NG denotes for natural restored grassland. On slope 1, the sampling points were numbered CK1 to CK9 from the bottom of the slope to the top; on slope 2, the sampling points were numbered CK10 to CK18, and from NG1 to NG 9 on slope 3 (Fig. 1). The distribution of the dominant species in the two shrub slopes was uniform. On the grass slopes, although the dominant species were Gramineae species, the distribution of individual species was more heterogeneous than that one the shrub slopes. Therefore, the sampling interval on the shrub slopes was greater than that on the grass slopes ensuring more representative sampling. Based on the actual length of the slope, the final distance between two adjacent sampling points was 20 m on the slopes with shrubs and 15 m on the grassland slope.

The deepest sampling depth was 5 m because the effect of artificial vegetation on soil moisture is deep in the Loess Plateau and the root

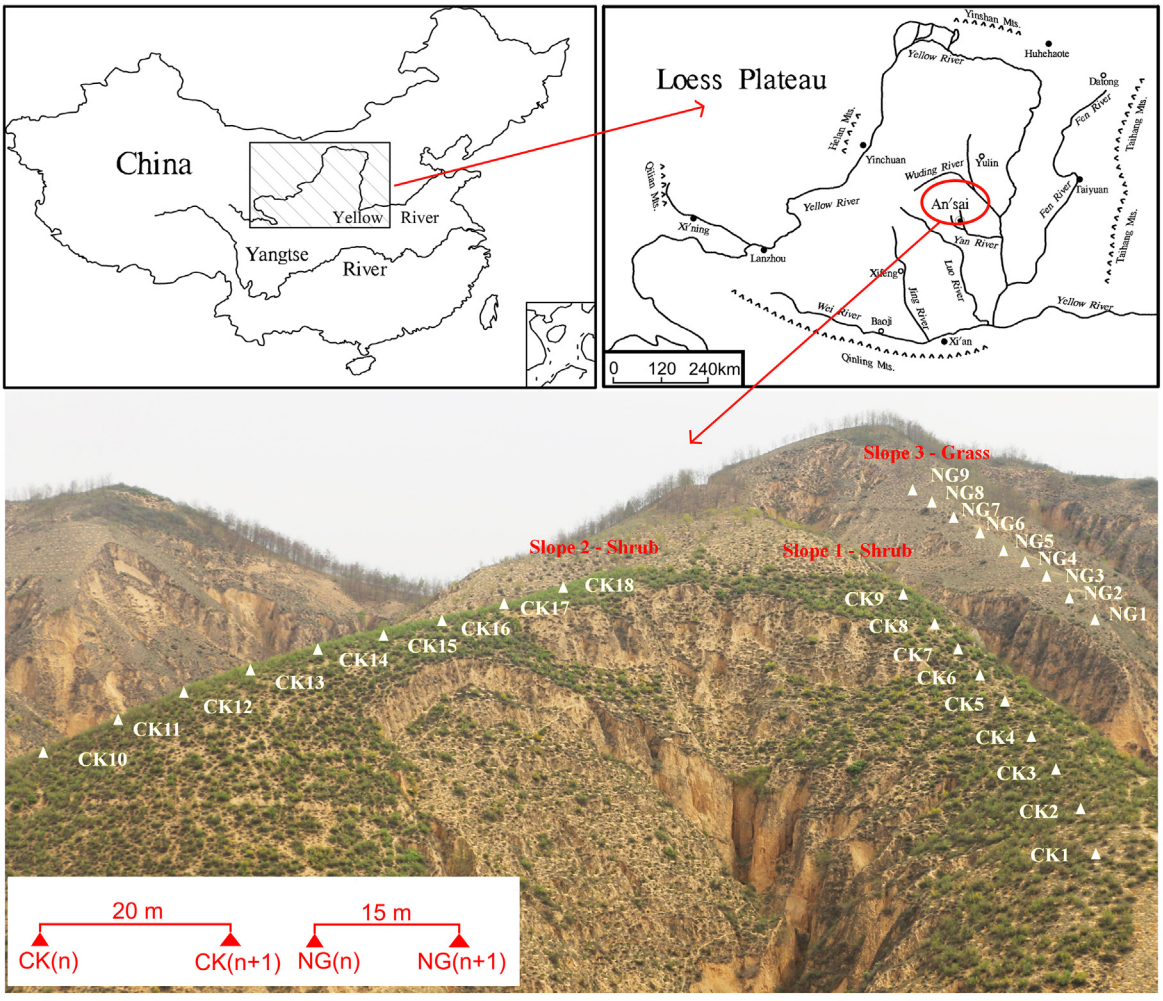

Fig. 1. Study area location map and photograph illustrating the distribution of soil sampling points. Notes: CK represents *Caragana korshinskii* shrubland, and NG represents natural restored grassland.

system range of most plants is generally concentrated at a depth of 0–5 m (Fang et al., 2016; Yang et al., 2014b). Samples were collected at 20-cm intervals between 0 and 1 m and at 100-cm intervals between 1 and 5 m. Three replicates per sampling point were collected using a soil auger with a 5-cm diameter, and each sample was divided into two parts. One part was placed in an aluminum box to measure the soil water content using the drying method at 105 °C, and the other part was used to determine soil particle size using a Mastersizer 2000 (Malvern Instruments Ltd., Worcestershire, United Kingdom) after removal of the organic matter and dispersion with H_2O_2 (10%), HCl (10%) and SHMP (sodium hexametaphosphate).

Undisturbed soil samples were collected on slopes 2 and 3 by excavating the soil profiles and using cutting rings at the top of the slope, the middle of the slope and the bottom of the slope. Samples were collected from four depth layers: 0–40 cm, 40–80 cm, 80–120 cm and 120–200 cm. Two cutting rings with different volumes were used simultaneously, and there were three replicates at each point. Soil samples collected with the 100-cm^3 cutting rings were used to determine bulk density with the drying method, and samples collected with the 200-cm^3 cutting rings were transferred into centrifuge tubes to determine the soil-water characteristic curves using a high-speed refrigerated centrifuge (CR2G, Hitachi Ltd., Tokyo, Japan) (Khanzode et al., 2002; Reatto et al., 2008). When the centrifugal force came to 1.5 MPa, the soil water content under this pressure is considered as the wilting point in the analysis (Shao et al., 2006).

The aboveground biomass was determined at the top, middle and bottom of each slope, and three replicated sampling plots were established at each position. The area of the plots was 5 × 5 m on the slopes with shrubs (slope 1 and slope 2) and 2 × 2 m on the slope with grass (slope 3). Plant samples were collected using the cutting method from 5 small subplots with a dimension of 20 × 20 cm that were randomly distributed in each plot and dried to a constant weight at 75 °C.

2.3. Data analysis

2.3.1. Fitting of the soil-water characteristic curve

The soil-water characteristic curve was fitted using the van Genuchten model (van Genuchten, 1980) according to Eq. (1), and the soil volumetric water content (cm^3/cm^3) was converted to soil mass water content (g/g) using Eq. (2):

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left(\frac{1}{1+(\alpha\times h)^n}\right)^m, \tag{1}$$

$$\theta=\theta_m\times\frac{BD}{\rho_w}, \tag{2}$$

where θ represents the soil volumetric water content (cm^3/cm^3); θ_m represents the soil mass water content (g/g); h represents the pressure head (cm); ρ_w represents the water density (ρ_w = 1.0 g/cm^3 in this study); θ_s and θ_r, represent the saturated and residual water content values, respectively, which were calculated from existing data; α, n and m are empirical parameters ($m = 1 - 1/n$ in this study) that also must be calculated from existing data (or termed model coefficients); and BD represents the soil bulk density.

2.3.2. Fractal analysis of soil particle-size distribution

The size of the soil particles was divided into clay (<2 μm), silt (2–50 μm) and sand (50–2000 μm) according to the USDA (United States Department of Agriculture) classification. Almost all of the soil samples were characterized as silt loam, and soil particles between 3.95 and 106.637 μm in size were represented in >80% of samples (Fig. 2, Supplementary 1). Using a combination of data from this study and standard practices from previous studies (Song and Li, 2011; Wang et al., 2007), soil particle sizes between 0.03 and 2000 μm were divided into 64 levels according to the logarithmic interval in the singular fractal analysis, while soil particle sizes between 0.3 and 1500 μm were divided into 64 levels according to the logarithmic interval in the multifractal analysis.

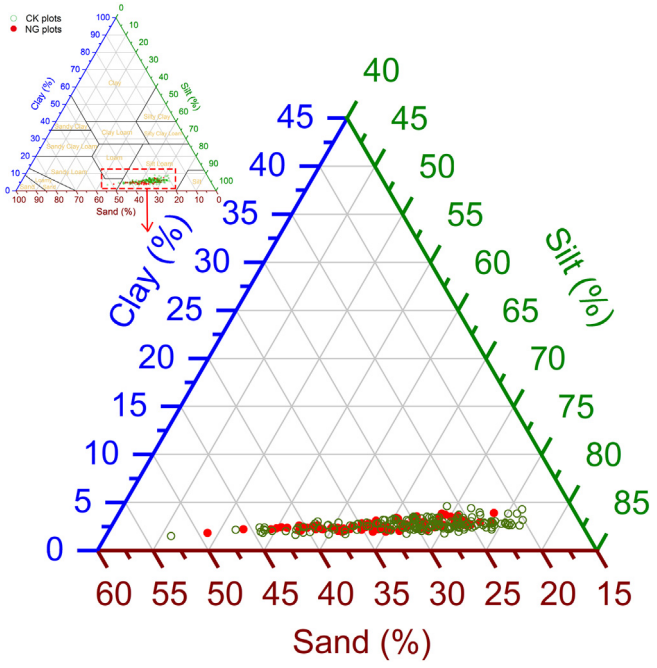

Fig. 2. Texture of the studied soil samples. Note: CK represents the soil under *Caragana korshinskii* Kom, and NG represents the soil under natural restored grassland.

The singular fractal dimension (F) of the soil particle-size distribution was calculated using Eq. (3). Logarithms were taken on both sides of Eq. (3) to obtain Eq. (4), and ($3 - F$) represents the slope of the logarithmic linear regression equation:

$$\frac{v(r<R_i)}{V_r}=\left(\frac{R_i}{R_{\max}}\right)^{3-F}, \tag{3}$$

$$\log\left(\frac{v(r<R_i)}{V_r}\right)=(3-F)\log\left(\frac{R_i}{R_{\max}}\right), \tag{4}$$

where $v\,(r<R_i)$ represents the cumulative percentage of particles with a radius less than R_i (mm); V_r represents the total percentage of particles (V_r = 100); R_i represents the particle radius (mm) of the i size class; and R_{max} represents the largest particle class radius (R_{max} = 2 mm in this study).

The multifractal dimension (Peitgen et al., 1992), which is also known as the Rényi dimension (Montero, 2005), of the soil particle-size distribution was calculated using Eq. (5) ($q \neq 1$) and Eq. (6) ($q = 1$).

$$D_q=\frac{1}{q-1}\lim_{\varepsilon\to0}\frac{\sum_{i=1}^{N(\varepsilon)}\mu_i(\varepsilon)^q}{\log(\varepsilon)}\quad(q\neq1), \tag{5}$$

$$D_1=\lim_{\varepsilon\to0}\frac{\sum_{i=1}^{N(\varepsilon)}\mu_i(\varepsilon)\log\mu_i(\varepsilon)}{\log(\varepsilon)}\quad(q=1), \tag{6}$$

where q represents the moment order of the distribution (q ranged from −10 to 10 with a 0.5 step interval in this study); $N(\varepsilon)$ represents the number of cells needed to cover the entire interval; ε represents the cell sizes; and $\mu(\varepsilon)$ represents the mass of the soil particles in this subinterval. When $q = 0$, the D_0 is called the capacity dimension (or the box-counting dimension), which accounts for the scaling properties and average information of a system, and it represents the dimension of the sizes that were set using a nonzero relative volume (the cell)

(Montero, 2005; Posadas et al., 2001; Voss, 1988). When $q = 1$, D_1 is known as the entropy dimension, which shows the scaling in the concentration of the parameter with cell interval and is related to the information or Shannon entropy (Andraud et al., 1994, 1997; Montero, 2005; Posadas et al., 2001; Shannon, 2001). When $q = 2$, D_2 is known as the correlation dimension and is mathematically associated with the correlation function. When the fractal is statistically or exactly self-similar and homogeneous, the equality $D_0 = D_1 = D_2$ occurs (Gouyet, 1996; Grout et al., 1998; Posadas et al., 2001).

2.3.3. Statistical analysis

Variations in the physical properties and water content of the soil at different slope positions and soil depths were analyzed by one-way analysis of variance (ANOVA), and the least squares difference method (LSDM) was utilized to verify the results. Correlations between the soil water content and the influencing factors were verified with Pearson's contingency coefficient (2-tailed; significant at $P < 0.05$; very significant at $P < 0.01$). After performing detrended correspondence analysis (DCA), the lengths of the gradient of the first axis were found to be shorter than 3.0; therefore, linear constraint-sorting redundancy analysis (RDA) was chosen to evaluate the correlations between each of the soil physical properties and water contents.

3. Results

3.1. Soil water content distribution and soil water-characteristic curve

The soil water content was constant at a lower level between 0 and 500 cm on the shrubland slopes (slopes 1 and 2) and between 0 and 100 cm on the grassland slope (slope 3), and soil water content increased with increasing soil depth. The difference in water content from the bottom of the slope to the top of the slope was not significant in the shallow layers, but the water content generally decreased from the bottom of the slope to the top of the slope in the 2–5-m layer. The soil water content at a depth of 0–100 cm was lower than that at 200–500 cm (LSDM, 0.05) on all slopes. The mean soil water content on the grassland slope was higher than that on the shrubland slopes at a depth of 0–500 cm, while the mean value on the grassland slope was lower than that on the shrubland slopes at a depth of 0–100 cm (Fig. 3).

Soil particle sizes were calculated, and the results are shown in Table 1. *D[3,2]* indicates the average particle size of a specific surface area, and *D[4,3]* indicates the average particle size of a volume surface area. The value of *R* (which equals *D[3,2]*/*D[4,3]* in this paper) was close to 1 when the shape of the particles became increasingly regular and the soil particle-size distribution became more centralized. In Table 1, d(0.1) indicates that soil particles of this size constitute 10% of all soil particles, d(0.5) indicates that soil particles of this size constitute 50% of all soil particles and d(0.9) indicates that soil particles of this size constitute 90% of all soil particles. The d(0.1), d(0.5), d0.9, *R*, and sand content values increased from the bottom of the slopes to the top, and the differences among the different positions were significant (LSDM, 0.05). The mean soil water content at the bottoms of the slopes was higher than that in the middle and at the top. According to a comprehensive analysis of *R*, d(0.5) and soil water content, particles in the lower slope position had a more regular shape and were smaller in average size than those in the upper slope position, while the soil water content in the lower slope position was higher than that in the upper slope position (Table 1).

Soil-water characteristic curves were fitted using centrifugation data and Eqs. (1) and (2). The results are shown in Fig. 4 and Table 2 and indicate that the van Genuchten model fits the sample data well. The wilting points on the slopes ranged from 0.52 g/g to 0.87 g/g, and the soil water content ranged from 0.24 g/g to 0.87 g/g. The wilting point

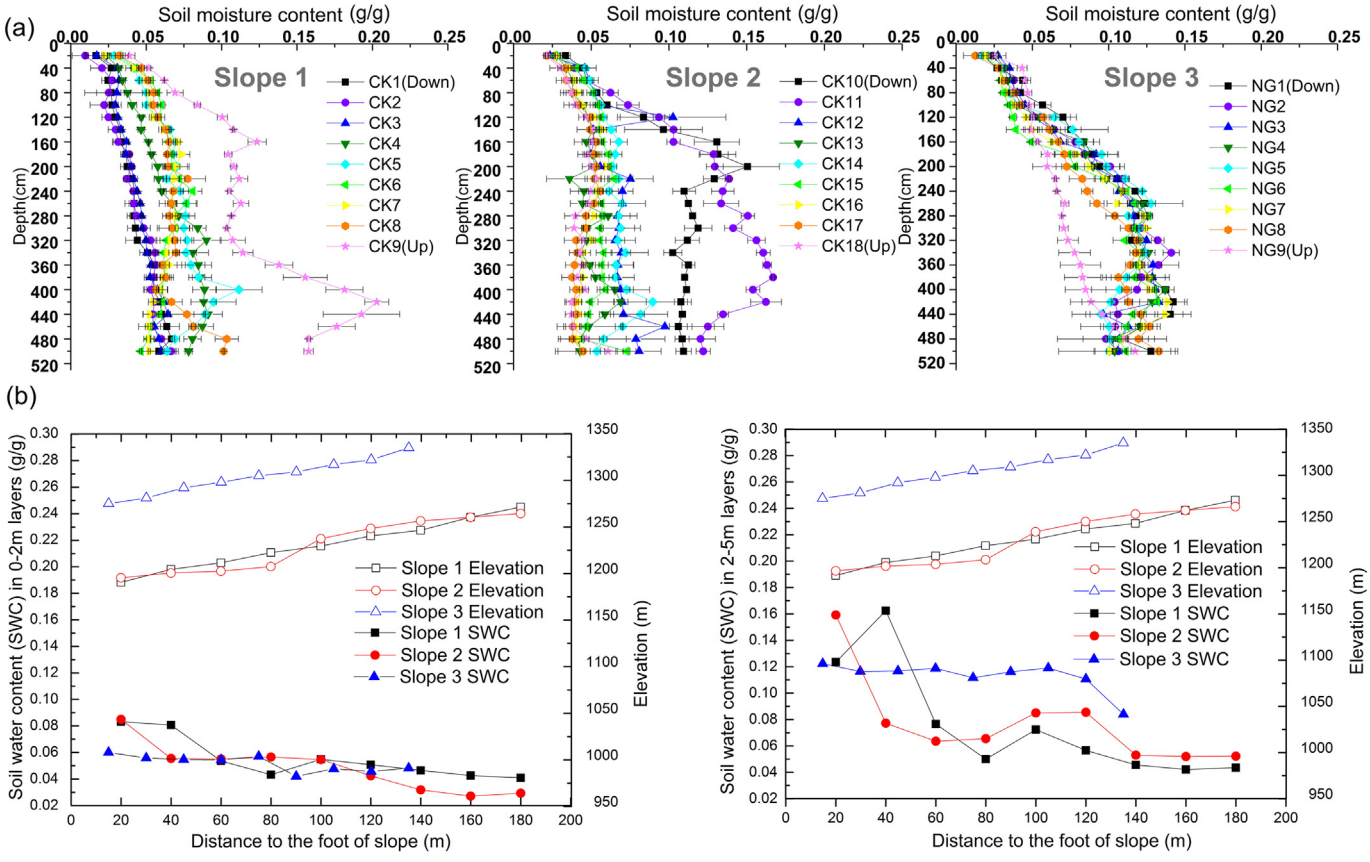

Fig. 3. Distribution of the soil water content at different depths (a) and different positions along the slopes (b).

Table 1
Soil property index values at different slope positions.

Index (unit)	Position	Mean value	95% confidence interval of mean		Min	Max
			Lower limit	Upper limit		
d(0.1) (μm)	Lower	3.69 ± 0.75a	3.53	3.86	2.31	6.03
	Middle	4.22 ± 0.79b	4.05	4.39	2.79	5.87
	Upper	4.59 ± 0.94c	4.39	4.80	3.11	7.01
d(0.5) (μm)	Lower	31.62 ± 4.54a	30.61	32.62	23.58	49.07
	Middle	33.90 ± 4.54b	32.90	34.90	25.38	44.25
	Upper	36.24 ± 5.52c	35.02	37.46	26.20	53.74
d(0.9) (μm)	Lower	77.69 ± 9.52a	75.58	79.79	31.55	104.72
	Middle	81.97 ± 8.57b	80.07	83.86	67.94	107.74
	Upper	85.86 ± 13.61c	82.85	88.87	67.45	173.82
R	Lower	0.21 ± 0.02a	0.21	0.22	0.12	0.26
	Middle	0.22 ± 0.02b	0.21	0.22	0.17	0.27
	Upper	0.22 ± 0.02b	0.22	0.23	0.17	0.28
Sand (%)	Lower	28.49 ± 5.45a	27.28	29.69	19.51	49.15
	Middle	30.99 ± 5.47b	29.78	32.20	21.28	43.65
	Upper	33.64 ± 6.59c	32.19	35.10	21.74	52.52
Silt (%)	Lower	68.49 ± 5.18a	67.34	69.63	49.01	76.65
	Middle	66.26 ± 5.25b	65.09	67.42	53.78	75.68
	Upper	63.78 ± 6.37c	62.37	65.19	45.81	75.31
Clay (%)	Lower	3.03 ± 0.60a	2.90	3.16	1.84	4.79
	Middle	2.75 ± 0.46b	2.65	2.85	1.94	4.14
	Upper	2.58 ± 0.43c	2.49	2.68	1.68	3.56
SWC (g/g)	Lower	0.07 ± 0.04a	0.06	0.08	0.02	0.19
	Middle	0.06 ± 0.03b	0.05	0.06	0.02	0.13
	Upper	0.05 ± 0.03b	0.04	0.05	0.02	0.13

Note: The same lowercase letters in the same columns indicate that the differences are not significant at the 0.05 level (one-way ANOVA and LSDM test; SWC represents soil water content). d(0.1) means the mass of the particles with sizes smaller than this value constitute 10% of the total mass; d(0.5) indicates the mass median diameter (MMD), which is also called the log-normal distribution mass median diameter; d(0.9) means the mass of the particles with sizes smaller than this value constitute 90% of the total mass; R indicates *D[3,2]/D[3,4]* (Sauter mean diameter / volume-based mean diameter) and the value following "±" is the standard error of the mean.

on the shrubland slope (slope 2) was higher than on the grassland slope (slope 3), while the soil water content on the shrubland slope was lower than on the grassland slope. On the shrubland slope, the soil water contents were lower than the wilting points in all soil layers, and on the grassland slope, the soil water contents were lower than the wilting points at depths between 0 and 120 cm.

3.2. Distributions of singular and multiple fractal dimensions on the slopes

The singular and multiple fractal dimensions were calculated using soil particle-size data and Eqs. (3), (4), (5) and (6), and the results are shown in Figs. 5 and 6. Fig. 5 shows that the logarithmic coordinates of the singular fractal dimension for each sample can form a line and that the lines for all the samples have two inflection points. The inflection points are close to the points that separate the soil into clay, silt and sand according to the Kaczynski classification system (0–1 μm, 1–50 μm, and 50–2000 μm, respectively); therefore, the lines are divided into three sections (the sand domain, the silt domain, and the clay domain) with significantly different slopes. The value of the singular fractal dimension (F) equals 3 minus the slope of the logarithmic linear regression line, and the F values are significantly different among these three domains. Overall, the singular fractal dimensions at different depths were more dissimilar on the grassland slope (slope 3) than on the other two slopes and were more dissimilar at the top of the slope than at the other positions. Fig. 6 shows the summary spectra of the multifractal dimensions at different positions and depths. In the Rényi dimension, $D_{(q)}$ decreased with increasing q. D_0 (box dimension) provides the basic soil particle size information, and it ranges from 0 to 1 as the soil particle size distribution becomes broader. D_1 (entropy dimension) provides a tool to describe the heterogeneity in soil particle size, and it increases with increasing heterogeneity. The combined index, D_1/D_0, better reflects soil particle size heterogeneity (Posadas et al., 2001), and D_2 (correlation dimension) also reflects the degree of uniformity.

The mean values of the singular and multiple fractal dimensions at various slope positions and soil depths are shown in Supplementary 2 and 3. Supplementary 2 shows that the singular fractal dimensions on the shrubland slopes increased from the top of the slope to the bottom, while the singular fractal dimension on the grassland slope changed irregularly. D_0 and D_1 first increased and then decreased from the top of the slope to the bottom, and *Fsilt* increased from the top to the bottom on the two shrubland slopes (slopes 1 and 2); however, the changes were not significant (LSDM, 0.05). Supplementary 3 shows that the mean values of D_1/D_0 on the two shrubland slopes (slopes 1 and 2) were lower than on the grassland slope (slope 3), but no differences in D_2 among these slopes were evident (Supplementary 2). Both the soil water content and the singular fractal dimensions first increased and then remained relatively stable as soil depth increased, and D_0 decreased and then remained relatively constant with increasing depth. D_1 and D_2 were higher at depths between 0 and 40 cm, below which they were lower and changed irregularly. D_1/D_0 in the 20–200-cm soil layers was lower than in the 300–500 cm layers (Supplementary 3).

3.3. Factors influencing soil water content and wilting point

Using the soil particle size, the soil water content data and the soil-water characteristic curves, the correlations between the soil water content and the factors *R*, sand content, silt content, clay content, *F*, *Fsand*, *Fsilt*, *Fclay*, D_0, D_1, D_2, bulk density, biomass, slope, and position were subjected to a 2-tailed test using Pearson's contingency coefficient (Supplementary 4). The species data were verified using a detrended correspondence analysis (DCA) (length of gradient <3), and the data gradient (Fig. 7) was then determined from the RDA of the soil water content at different depths and other factors described in Supplementary 4. Supplementary 4 and Fig. 7(b) show that the soil water content was significantly positively correlated with silt content, clay content, *F* and depth, while it was significantly negatively correlated with sand content. The wilting point was significantly positively correlated with silt content, clay content, depth and biomass, while it was significantly negatively correlated with sand content. Among the other factors, D_0, D_1 and D_2 all had significant negative correlations with bulk density, while *R* had a significant positive correlation. The values of D_0 and D_1 increased with increasing sand content and decreasing in silt content and *R*. *R* was significantly positively correlated with silt content (Supplementary 4, Fig. 7).

The relationships between soil water content and the relevant factors at different depths are shown in Fig. 7(a). The soil water content had a positive correlation with silt content, clay content, F_{sand} and *F* in the 0–100 cm soil layers, and it had a positive correlation with position, D_1, D_2, D_{silt} and slope in the 200–500 cm soil layers. The soil water content was negatively correlated with sand content in the 0–100 cm soil layers and with *R* in the 200–500 cm soil layers. Biomass exhibited a positive correlation with soil water content in the 0–100 cm soil layers, but the relationship was negative in the 200–500 cm soil layers (Fig. 7).

4. Discussion

4.1. Spatial variation in soil water and wilting point at the transect scale

There is a long history of soil water content research on the Loess Plateau. After many years of vegetation restoration, the soil water conditions have changed considerably. A previous study in a normal year (Fang et al., 2016) and our study in a drought year (Fig. 3) have both shown that the soil water content is lower under CK than under NG.

At various depths, the differences in soil water content between shrubland and grassland increased from the top layer to the deeper layers of the soil profile, and the average soil water content was higher

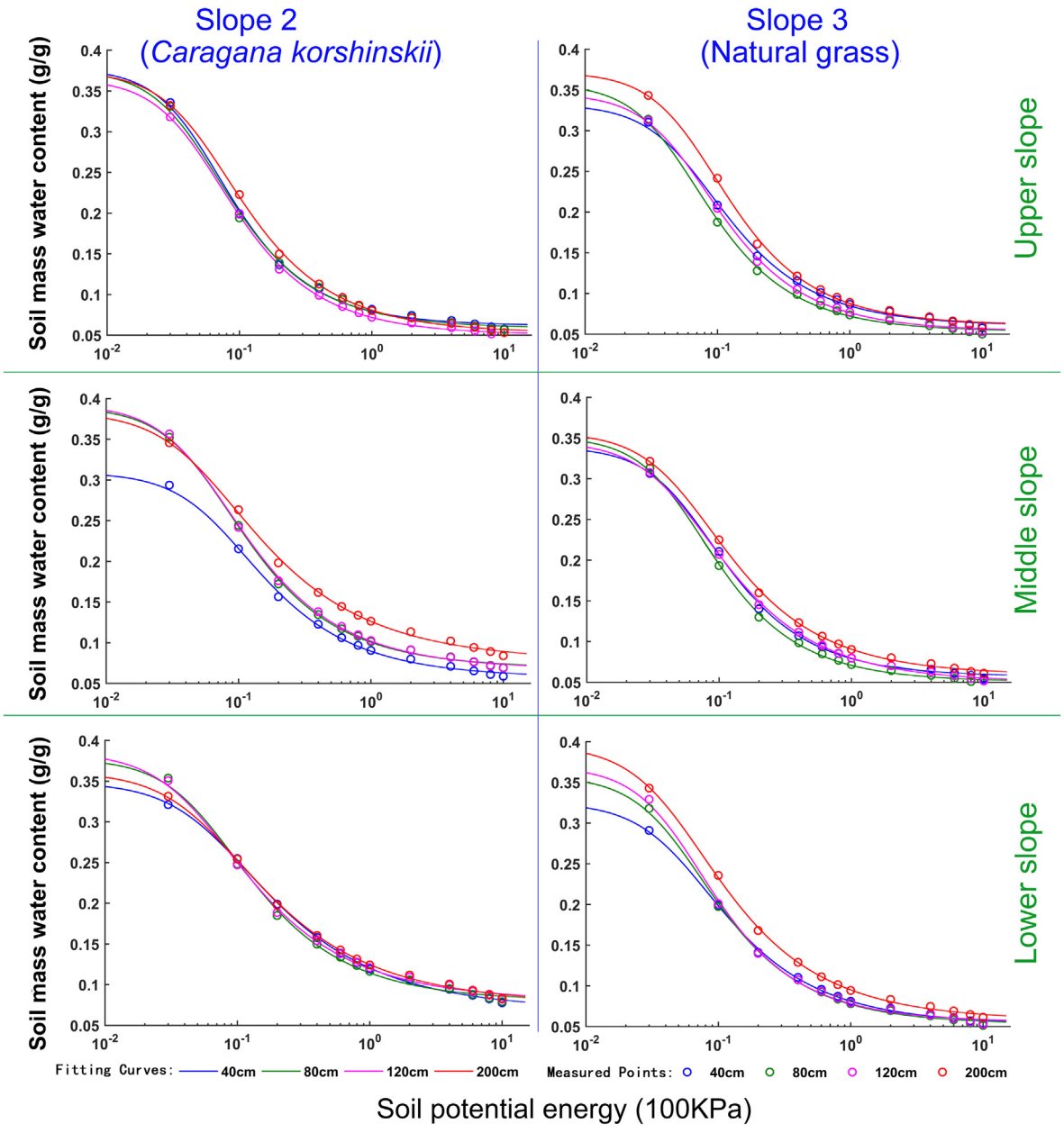

Fig. 4. Soil-water characteristic curves at different slope positions and soil depths.

in the shallow layers (0–2 m) than in the deep layers (2–5 m) in normal years (Liu et al., 2016b; Zhang et al., 2016a, b). During a drought year, the shallow soil layers receive little rainfall, and evapotranspiration and root uptake resulted in less soil water content in the 0–2 m soil layers than in the 2–5 m layers (Fig. 3).

At various slope positions, from top to bottom of the slope, the soil water content typically increased, but this relationship can change as the slope increases (Gao et al., 2011; Huang et al., 2013). In this study, the soil water content decreased inconsistently from the bottom of the slope to the top and remained low at all positions, but the degree of change was smaller in the shallow layers (0–2 m) than in the deep layers (2–5 m) in the drought year (Fig. 3, Table 1). This may imply that it is difficult for water loss to continue due to the lower soil water content in the shallow layers; CK seemed to use less water from the shallow soil layers (0–1 m) under drought conditions. In deep soil layers below 2 m, the increase in amplitude was higher in NG than in CK during a drought year (Fig. 3) and was similar to that of normal years (Zhang et al., 2016a, b). The variation in soil available water content and the variation in soil water content were similar to each other along the slopes. Soil water content at the depth of 0–2 m under CK and at 0–1.2 m under NG was lower than the wilting point. The only available soil water that could be used by CK was below 2 m, but the soil water that could be used by grass was below 1.2 m during the summer in a drought year (Table 2). As dry years might occur more frequently in the future, introduced shrubs such as *Caragana korshinskii* would have a negative effect on vegetation restoration in drylands with thick soil layers and deep ground water.

4.2. Spatial variation in the soil particle size distribution at the transect scale

The soil particle-size distribution has been found to be essential to the formation of soil structure and soil nutrient conservation (Jiménez et al., 2008; Liu et al., 2016a; Marques et al., 2015; Peng et al., 2015; Song et al., 2015; Sun et al., 2016a; Yu et al., 2015a). Fine particles smaller than 50 μm (clay and silt) retain soil organic carbon better

Table 2
Fitting parameters, wilting points, soil water contents and bulk densities of the soil samples.

Position	Depth (cm)	Fitting parameters				Wilting point (g/g)	SWC (g/g)	Bulk density (g/cm^3)
		θ_s	θ_r	α	n			
Slope 2								
Upper slope	0–40	0.06	0.38	20.74	1.95	0.06	0.02	1.353
	40–80	0.06	0.38	22.16	1.88	0.06	0.03	1.34
	80–120	0.05	0.37	21.11	1.88	0.05	0.03	1.38
	120–200	0.05	0.37	18.99	1.83	0.06	0.04	1.33
Middle slope	0–40	0.06	0.31	14.39	1.77	0.06	0.04	1.28
	40–80	0.07	0.39	18.38	1.80	0.07	0.05	1.29
	80–120	0.07	0.39	19.01	1.76	0.07	0.05	1.30
	120–200	0.08	0.38	19.33	1.62	0.09	0.06	1.33
Lower slope	0–40	0.07	0.35	15.50	1.61	0.08	0.04	1.32
	40–80	0.08	0.38	17.27	1.75	0.08	0.06	1.33
	80–120	0.08	0.39	20.09	1.68	0.09	0.07	1.35
	120–200	0.08	0.36	17.58	1.62	0.09	0.08	1.37
Slope 3								
Upper slope	0–40	0.06	0.33	16.79	1.85	0.06	0.03	1.08
	40–80	0.05	0.36	21.54	1.91	0.06	0.04	1.26
	80–120	0.05	0.35	18.15	1.88	0.06	0.05	1.37
	120–200	0.06	0.37	15.46	1.90	0.06	0.09	1.33
Middle slope	0–40	0.06	0.34	17.30	1.89	0.06	0.03	1.34
	40–80	0.05	0.35	19.87	1.91	0.05	0.03	1.42
	80–120	0.05	0.35	19.63	1.77	0.05	0.04	1.36
	120–200	0.06	0.36	18.39	1.77	0.06	0.08	1.33
Lower slope	0–40	0.05	0.33	19.53	1.76	0.06	0.03	1.23
	40–80	0.05	0.36	20.89	1.83	0.06	0.04	1.36
	80–120	0.06	0.37	20.67	1.87	0.06	0.05	1.45
	120–200	0.06	0.40	22.09	1.71	0.06	0.08	1.35

Note: θ_s, θ_r, α, n are fitting parameters in the van Genuchten model (Eq. (1)); SWC represents soil water content.

than coarse sand; therefore, nutrient and soil organic carbon losses mainly occur because of the loss of clay and silt from soils (Jin et al., 2013; Wang et al., 2007; Zhao et al., 2014). In this study, fine particles increased and coarse particles decreased from the top of the slope to the bottom of the slope (Table 1). Therefore, the shape of the soil particles became more uniform, and d(0.5) increased while the water-holding capacity decreased from the bottom of the slope to the top (Table 1). When water flows from the top of the slope to the bottom of the slope under a normal erosion process, fine particles are removed first as they are more easily eroded than coarser particles, and during this movement, these particles become ball-shaped as their surfaces are smoothed (Table 1). As more fine particles move to the lower position of the slope, the average soil particle size is smaller than that in the upper slope (Supplementary 1 and Table 1). Existing studies have shown that different kinds of plants might have different influences on soil texture and properties (Cortina and Maestre, 2005; Gu and Luo, 2016; Li et al., 2012). For example, the conversion from cropland to other types of vegetation in the Loess Plateau was more effective for improving soil conditions in deep soil layers (Sun et al. 2016b), while studies in the northern part of the Loess Plateau showed that conversion from cropland to shrub or grass land worsened water conditions in the deep soil profile (Zhang et al. 2018). In this study, more fine particles were found in shrublands than grasslands, indicating that shrublands were more efficient at trapping the fine sediments, protecting fine soil particles better than grasses (Supplementary 1).

The values of F_{clay} were found to be lower than 0 in previous studies (Wang et al., 2007) as well as in this study (Supplementary 2), which means that the data from the laser particle-size analysis are not very accurate for the clay domain. However, analyses of other domains have proven to be useful in discussing the soil particle distribution and fractal dimensions (Bai and Wang, 2012; Dong and Zheng, 2010; Ru et al., 2015). Existing studies show that indices such as F, F_{silt}, F_{sand}, D_0, D_1,

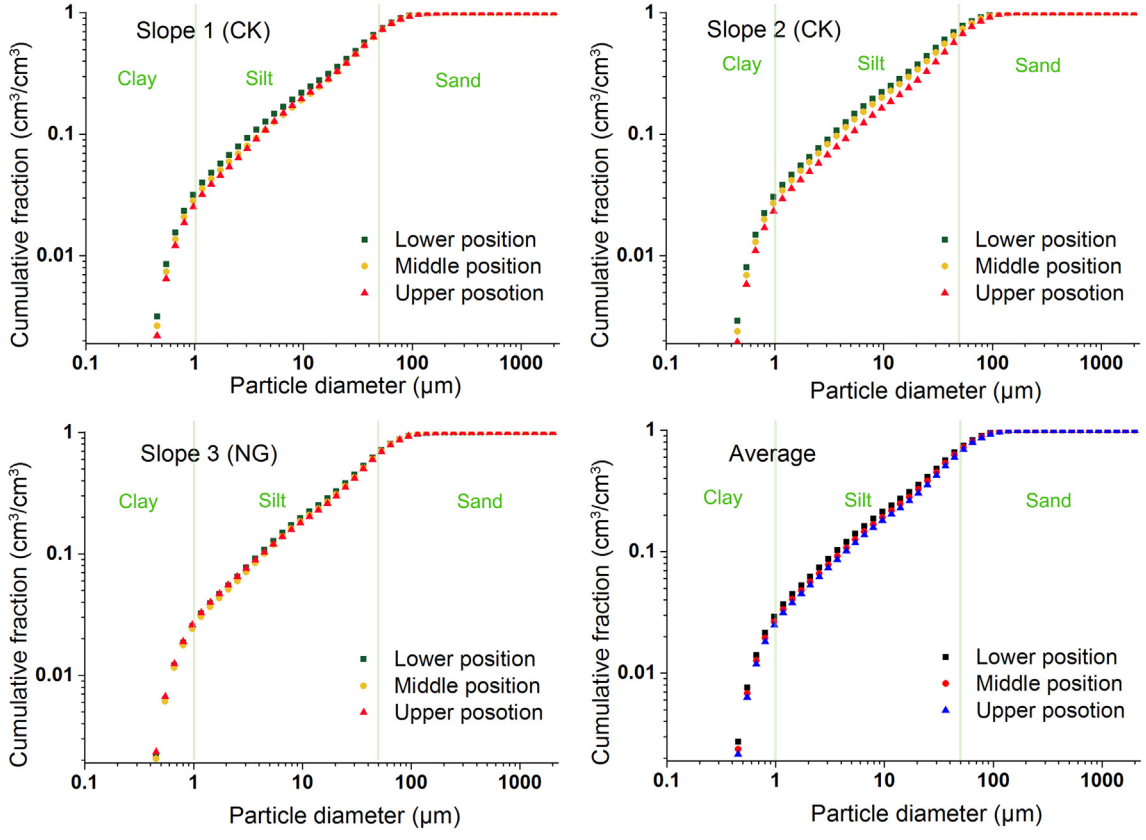

Fig. 5. Log-log plots of soil particle size distributions for samples at different depths and slope positions.

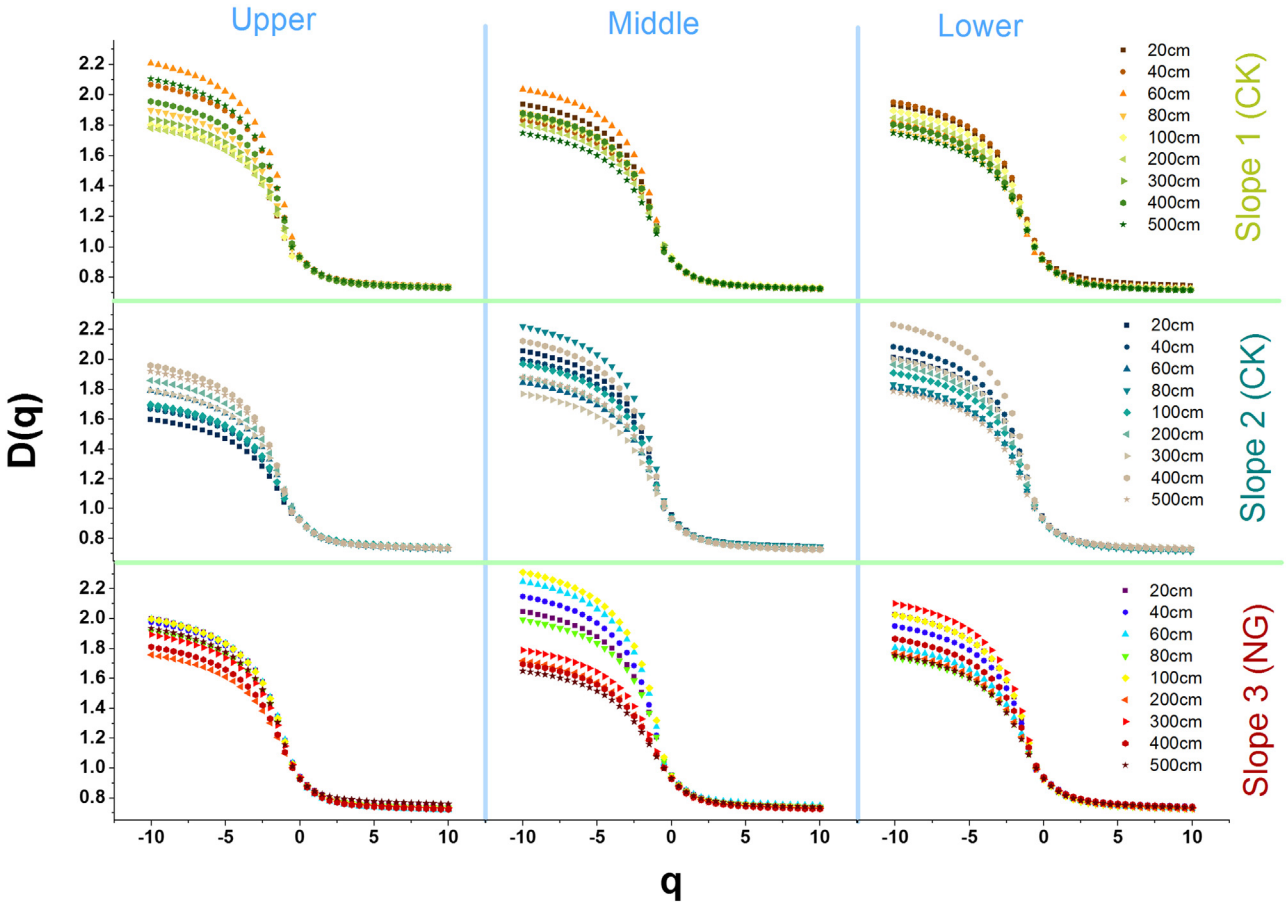

Fig. 6. Multifractal Rényi spectra *Dq*-q curves of soil samples from different depths and slope positions.

D_2 and D_1/D_0 highly correlate with soil organic matter, and these measures can potentially be used to reflect soil quality (Marinho et al., 2017; Wang et al., 2007; Zaffar and Lu, 2015; Zhang et al., 2012a, 2012b). These indices also differed at different slope positions and soil depths in this study. As the depth increased, the soil water content, *F*, and F_{sand} increased, while D_0 decreased (Supplementary 3). The D_1 and D_2 values in the 0–40-cm soil layers were higher than in the 60–500-cm soil layers, which means that there were more differences among the soil particles in shallow layers than among those in deep layers (Supplementary 3). As fine particles are more easily removed by runoff or soil water movement than are coarse particles, the range of the soil particle-size distribution was larger at the bottom of the

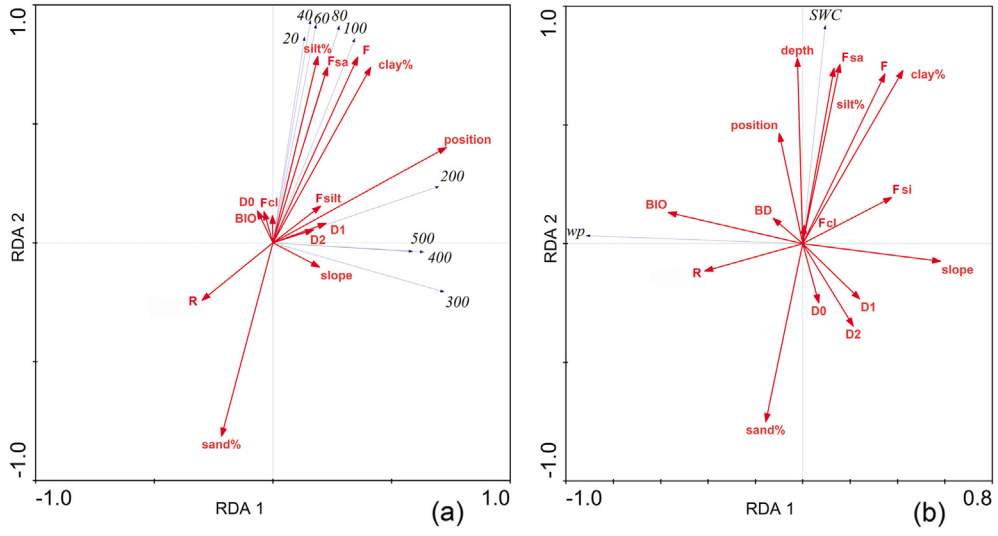

Fig. 7. Relationships between soil water content and the relevant factors (a) at different depths, as well as the relationships between soil water indices (soil water content and wilting point) and the relevant factors (b). Note: Sand% represents sand content; silt% represents silt content; clay% represents clay content; Fsa represents *Fsand*; Fsilt represents *Fsilt*; Fcl represents *Fclay*; BIO represents biomass; R represents *D[3,2]/D[3,4]*; SWC represents soil water content; wp represents the wilting point; and the numbers 20, 40, 60, 80, 100, 200, 300, 400, 500, etc. in the left figure (a) represent the soil layer depth (cm).

slope than at the top on the two shrub slopes (Table 1 and Supplementary 2), whereas on the grass slope, the F, D_0, D_1 and D_2 values at the middle position were lower than those at the other positions (Supplementary 2). These changes occurred not only on the soil surface but also in the different soil layers (Fig. 6 and Supplementary 3). Therefore, CK should be planted lower on the slope, and NG should be restored in the upper slope position to maintain the sustainability of vegetation restoration in this area.

4.3. Correlations between soil particle size and soil hydraulic parameters

Soil physical, pedological and hydrological properties are intrinsically connected (Lin, 2010; Montenegro and Ragab, 2012; Venkatesh et al., 2011; Vivoni, 2012; Yao et al., 2012; Zhao et al., 2011). The wilting point obtained from the soil-water characteristic curve showed significant correlations with F, clay content, silt content and F_{sand}, which indicates the feasibility of using fractal dimension parameters to estimate wilting point (Fig. 7, Supplementary 4). The wilting point had a stronger correlation with clay content than with biomass, whereas the correlation between the wilting point and biomass was significant at the 0.01 level (2-tailed) (Supplementary 4). This correlation may exist because there is little variation in clay content over small scales at which the influences of the vegetation appear. This result suggests that clay content rather than vegetation condition is the main factor correlated with the wilting point, and the fitting efficiency of the clay content to the wilting point is very good in practice (Wang and Shao, 2000).

Clay content is more strongly correlated with fractal dimension than is silt content or sand content. Both cultivation and natural movement by wind, water or gravity impact the soil particle-size distribution (Dong and Zheng, 2009; Gui et al., 2010; Wang et al., 2007; Xia et al., 2015; Zhao et al., 2015). The singular dimension has a stronger correlation with position at the transect scale, while the multiple dimension has a stronger correlation with the gradient (Supplementary 4). Biomass shows a significant correlation with soil particle size uniformity, F in the silt domain and F in the clay domain, which also indicates that fine particles have a greater impact on plants than coarse particles (Supplementary 4). In addition, the impact of biomass on wilting point is greater than its impact on soil water content, and biomass has a positive correlation with soil water content in the 0–1-m soil layers and a negative correlation in the 2–5-m soil layers (Fig. 7), indicating that greater plant biomass could reduce soil water loss in shallow layers through reduced evaporation while increasing soil water consumption in deep soil layers.

Fractal dimensions have been used to estimate the soil-water characteristic curve, which simplifies the fitting process (Tyler and Wheatcraft, 1989, 1990, 1992; Zheng et al., 2012). In this study, although the overall simulation results are good, some of the modeled soil water content conditions in the lower layers are slightly higher than the measured values (Fig. 4). While it is feasible to study the relationships between soil properties and soil hydraulic properties using this approach, the model must be calibrated under different soil water contents and soil particle-size distributions.

5. Conclusion

Research on ecological restoration is important on the Loess Plateau of China because of the severe soil and water conservation challenges in this region. In the context of global climate change, the frequency of extreme weather years (drought or flood) may increase. The soil water content and soil particle-size distribution on the sampled slopes vary with position along the slope and with soil depth. From the upper part of the slope to the lower part, soil water content increases inconsistently, and the singular fractal dimension and D_0 positively correlate with the soil water content on the shrubland slopes, while these changes are not consistent on the grassland slope. From the shallow soil layers to the deep soil layers, the change in singular fractal dimension is positively correlated with soil water content, while D_0 is negatively correlated with soil water content with increasing depth. The biomass exhibits a positive correlation with soil water content in the 0–100-cm soil layers, but the correlation becomes negative in the 200–500-cm soil layers. The change in the wilting point is related to both biomass and the proportion of fine soil particles at the transect scale.

Estimation of the soil-water characteristic curve using easily obtainable soil parameters is feasible. During a drought year, the soil water that can be used by *Caragana* is below 2 m, while the soil water that can be used by grass is below 1.2 m. Although CK has greatly contributed to local soil and water conservation in the last century, extensive and long-term planting of this shrub species is not suitable for sustainable vegetation restoration on the Loess Plateau as the climate may change due to both future warming and drying conditions. For south-facing slopes, which have lower soil water contents than the north-facing slopes, leaving the upper slope to naturally revegetate with grasses to maintain soil water while planting CK lower on the slope to retain fine soil particles may be a better vegetation restoration approach. This special region of drylands occupies a large area; therefore, these suggestions to balance water consumption and soil erosion might be used for vegetation restoration in other semiarid areas with thick soil layers and deep ground water.

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Appendix A. Tables for the details

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.08.211.

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